ELECTRICAL POWER SYSTEM HEALTH MANAGEMENT

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Abstract

One of the most critical systems in any aerospace vehicle is the electrical power system. Comprised of energy generation, energy storage, power distribution, and power management, the electrical power system (EPS) is relied upon by every major subsystem for proper operation. In order to meet the safety requirements of aeronautics and space systems - and provide for their reliability, maintainability, and supportability - advanced health management (HM) techniques for electrical power systems are required. A detailed review of the major EPS component failure modes shows that power generation and energy storage components generally employ some basic HM techniques to estimate and manage remaining life. However, power management and distribution components and systems employ almost no on-board HM techniques. A survey of current aerospace vehicles and platforms will show that power HM systems have employed simple performance and environmental monitoring to provide indications of possible component and subsystem failures, and used redundant components as a "safety-net" when failures do occur. More advanced methods that detect fault locations in wiring are used for maintenance purposes and not as an on-board safety system. In order to move beyond this, future power HM systems need to be "intelligent" and operate autonomously. This means that they need to be able to detect and isolate incipient faults, mitigate failures, or predict impending failures so that mitigating actions can be taken. The historical method of "adding" on HM capabilities after a system has been developed leads to high cost for implementation, limited capabilities, and low reliability in operation. Future aerospace power systems need to incorporate HM capability early in the design cycle for maximum benefit.

Introduction

It can be argued that no other aerospace subsystem is as critical as the Electrical Power System (EPS). All critical flight systems - life support, propulsion, guidance, navigation, communications, and science - all depend on a reliable source of electrical power. Advanced power system technologies, including health management, will enable the future success of long duration space flight missions, new aircraft, new launch vehicles, and operation of surface- or space-based stations.

The EPS is a complex, highly interconnected system that requires many diverse technical disciplines for effective operation. The EPS can be broken into four major functional elements:

Energy Conversion/Generation – solar arrays, fuel cells, generators, nuclear, etc.
Energy Storage – batteries, flywheel, thermal, etc.
Power Distribution – regulators, switchgear, converters, and cables
Power Management – command, control, and EPS data acquisition

Energy generation and energy storage work hand-in-hand to provide the critical source of electricity. The power management and distribution (PMAD) system can be thought of as the "electric utility", providing the regulation, cables, switches, and controls necessary to safely and reliably deliver power from the sources to the loads. Since each of these subsystems are relied upon to provide electricity, the detection and isolation of faults and degradation throughout the entire electrical power system is inherently important to the overall function, safety, and reliability of the entire system.

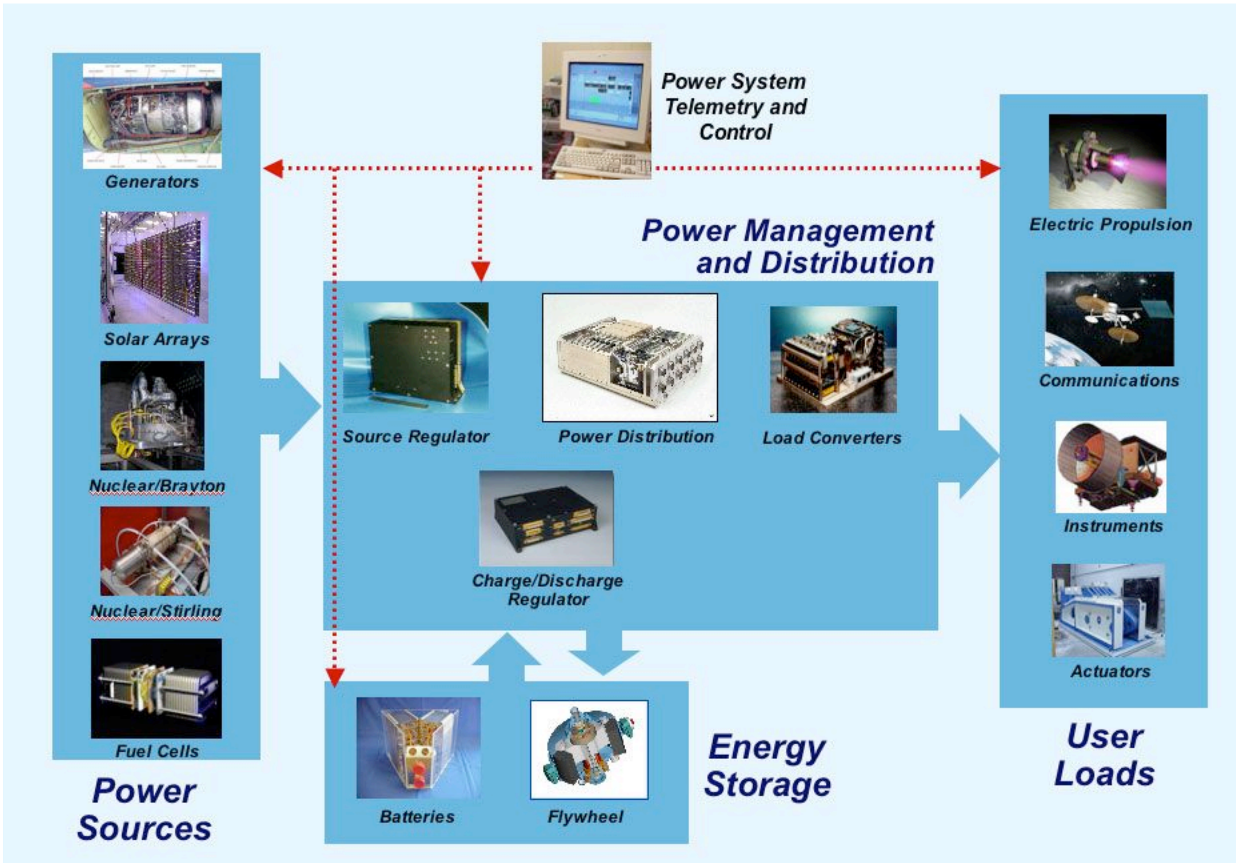


Figure 1 – Aerospace Power System Block Diagram

This paper is divided into three main sections. The first section presents a summary of the typical failure modes for some common electrical power system components. Specifically, this covers the following: solar arrays, fuel cells, batteries, flywheels, and PMAD. A description of the mechanisms that lead to the failure mode and how that failure mode is detected and diagnosed are presented for some frequently used EPS components. In the second section, existing capabilities in power system HM are discussed. This section begins by providing space-related HM state-of-the-art examples (Hubble Space Telescope, the International Space Station, and the Space Shuttle) followed by aeronautic examples. Finally, the current and future capabilities that will be required of power system HM are discussed with an emphasis on hardware and software technologies in order to make future power system HM a successful application.

Summary of Major EPS Components and their Failure Modes

This section describes the major elements of the Electrical Power System and some major failure modes that may be encountered during operation. Discussion of failure and degradation detection and recovery is presented where applicable. Energy conversion (solar arrays and fuel cells), energy storage (batteries and flywheels), and power management and distribution (PMAD) are presented below.

Solar Arrays

Solar arrays are comprised of many solar cells on a common structure that generate electrical energy in proportion to the amount of solar insolation (light energy) they receive. The arrays can be either body-mounted on the spacecraft or deployed via rigid panels or flexible, fan-fold sheets. The solar cells are connected in series "strings" to meet the electrical voltage requirements of the spacecraft. The strings are then connected in parallel to meet the total power requirements.

Complete failures of solar arrays are very rare or non-existent. Complete failure modes include deployment mechanism failure or physical separation of the entire deployed array. These failures are easily detected by the complete lack of electrical power from a single solar array wing or panel.

Most array failure modes simply lead to a reduction in array performance. These can include cell and string failures, sun tracking and pointing failures, and cell degradation. Array cells and strings can fail for a number of reasons, including micrometeoroid damage, high voltage arcing, and failures of array regulator power electronics. If the array is properly designed with cell bypass diodes and string reverse-blocking diodes, the failure of a single cell or string will have little effect on mission safety or effectiveness. A more pressing concern for solar arrays is that of degradation. Array degradation can occur over time due to radiation effects, array contamination from arcing and sputtering of metals, dust accumulation (for surface systems), and/or clouding of the protective cell coverglass.

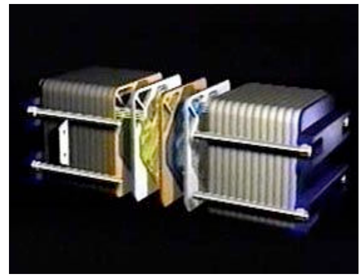
Failure/Degradation	Mechanisms	Detection	Diagnosis
Solar panel failure	Deployment failure, mechanical separation	Array current/voltage sensor, insolation sensor.	Zero current/voltage output with good insolation.
String failure	Micrometeoroid damage, cable failure, shadowing	String current/voltage sensor, insolation sensor	Zero string current/voltage output with good insolation.
Cell failure	Micrometeoroid damage, shadowing	String current/voltage sensor	Degraded string performance in relation to others.
Array pointing failure	Array drive lockup, loss of spacecraft attitude control	Sun sensor, array insolation sensor	Lower than expected array power, lack of sun tracking.
Array degradation	radiation damage, contaminates, cover glass clouding	Array current/voltage sensor, insolation sensor. IV curve test	Historical trend data showing reduced power at equivalent insolation.

Table 1 – Solar Array Failure Mode Summary

Failure Recovery and Health Management - Since each solar array is naturally segmented, there is already inherent fault tolerance of the entire array to most failure events. Complete array failure is non-recoverable, as are partial array failures. However, spacecraft usually employ two solar arrays, and they are normally designed to mitigate partial array failures and ensure that the failure does not propagate to other parts of the array.

Array health and degradation are the most pressing concerns for EPS health management systems. In general, health measurement capabilities are in use today. Array performance trending over time is crucial for detecting accelerated degradation and being able to take corrective actions or plan for energy balance problems in the future. These capabilities are typically ground-based using historical array performance telemetry data to estimate array health and project future capabilities. Based on these calculations, long-term mission planning can be adjusted to accommodate expected changes (positive or negative) in array performance.

Fuel Cells



Fuel cells convert chemical energy in the form of hydrogen and oxygen (the reactants) into water, electrical energy, and heat. Since the fuel cell requires a constant flow of reactants, total energy is only limited by the amount of hydrogen and oxygen storage available. There are two major types of fuel cells used in aerospace systems – proton exchange membrane (PEM) and alkaline fuel cells. The Space Shuttle uses alkaline fuel cells with an asbestos membrane saturated with a liquid potassium hydroxide electrolyte, while PEM fuel cells use a solid per-fluorinated ionomer membrane. PEM technology has been developed for commercial applications, and its safety and operation advantages make it an attractive solution for new aerospace power systems.

A fuel cell is typically constructed as a number of cells connected in series – this is called the fuel cell stack. The number of cells in the stack determines the output voltage of the fuel cell. The cross-sectional area of each cell determines the current density, and hence the power (V*I), that the fuel cell can provide. Aside from the actual fuel cell, reliable operation depends on a multitude of ancillary components necessary to control the flow of the reactants into the fuel cell, and removal of water and excess gas from the fuel cell. These ancillary components include reactant storage tanks (usually cryogenic), pumps, valves, pressure regulators, feed lines, water separators, and thermal control systems.

Fuel cell system failures range from failures in the ancillary components to failures of one or more actual cells. Since the cells are connected in series and the reactants are fed into each cell using hydrogen and oxygen manifolds, a failure of any ancillary component or cell will force the shutdown of the entire stack. A summary of fuel cell failure and degradation mechanisms is shown in Table 2.

Failure/Degradation	Mechanisms	Detection	Diagnosis
Cell reactant crossover	Failure or leak of the reactant separator in a cell.	Cell voltage, stack temperature, and pressure.	Gradual loss of cell and/or stack voltage; rapid loss indicates complete cell failure.
Cell flooding	Excess water in cell blocks reaction sites.	Cell voltage, stack temperature, and pressure.	Gradual loss of cell and/or stack voltage.
Cell degradation	Changes to catalyst and membranes over time.	Cell voltage and stack temperature.	Degradation in cell and/or stack voltage over time. Weak cell affects entire stack.
Ancillary failures	Pressure regulator failure, line leaks, valve failure	Pressure and temperature sensors	Pressure and temperature hard-limits set by system design requirements.

Table 2 – Fuel Cell Failure Mode Summary

Failure Recovery and Health Management – Most fuel cell failures are non-correctable since the ancillary system and stack designs do not allow for the isolation of a failed component. However, cell flooding is one problem that can be corrected using valves that purge the fuel cell of excess water and/or reactant contaminants and restore stack operation to nominal levels. While some stored reactants are lost during this purging cycle, fuel cell power delivery is maintained.

Generally, fuel cell health management capability exists today and is essentially required for safe operation. The stack will have individual cell voltage sensors in order to detect a cell failure, and a current sensor will be used in conjunction with the voltage sensors to determine fuel cell output power. The relative health of the individual fuel cells will be reflected in the cell voltage measurements.

The ancillary feed system will rely on many pressure, temperature, and flow meters to ensure that reactants are properly flowing through the system. While these sensors are used mostly for hard limit shutdowns, they can detect early problems with the fuel cell system that can be corrected using closed-loop controllers that activate heaters, purge valves, thermal control systems, water separators, and pressure regulators. Interconnected, intelligent algorithms coupled with these ancillary systems can optimize fuel cell performance and health. Additionally, manned vehicles may employ hydrogen and oxygen sensors to ensure that there are no unexpected reactant leaks, especially into pressurized environments.

Batteries

Battery cells are electrochemical devices that store energy. There are two classes of batteries – primary and secondary. These classifications are based upon the reversibility of the cell chemistry. Primary batteries are non-rechargeable, one-time use. Secondary batteries are rechargeable. Both primary and secondary batteries are used for aerospace-related applications, depending upon the requirements of the particular vehicle or mission.

Primary chemistries that have been used or are under development for aerospace applications include zinc-manganese oxide ($ZnMnO_2$), lithium sulfur dioxide ($LiSO_2$), lithium-carbon monofluoride ($LiCF_x$), lithium-thionyl chloride ($Li\text{-}SOCl_2$), and thermal batteries. Primary batteries can be found where a reliable source of electricity is only needed for short periods of time, such as expendable vehicles, serviceable systems (such as launch vehicles and the space shuttle), probes, and pyrotechnic events.

Secondary aerospace batteries use chemistries such as silver-zinc (AgZn), nickel-cadmium (Ni-Cd), nickel-hydrogen ($Ni\text{-}H_2$), nickel metal hydride (Ni-MH), or lithium-ion. Secondary batteries are commonly used in orbiting spacecraft where cyclical periods of sunlight and eclipse require the use of rechargeable batteries to power the spacecraft during eclipse periods. Both primary and secondary batteries have been used on landers and rovers. A combination of primary and secondary batteries are used on extravehicular activity suits.

Batteries are comprised of individually packaged cells connected in series and parallel configurations to obtain the desired voltage and capacity. Cells can range in capacity (ampere-hours, or Ah) from large 350 Ah high-pressure vessels for NiH_2 cells, to small 2.0 Ah cylindrical lithium-ion cells (18650) that can be found in consumer electronics, to even smaller cells in the milliampere-hour capacity range.. A battery is only as strong as its weakest cell. Battery failures are often caused by a single cell failure, and performance degradation can be the result of a single poor performing cell. In order to maximize life and performance, aerospace cells and batteries undergo a rigorous certification and qualification program in both manufacturing and testing prior to flight assembly to ensure that the battery is performing as expected and that each cell is well balanced with the entire lot.

Each battery chemistry presents different safety and performance concerns. For example, lithium-ion batteries are very sensitive to overcharging, so special care must be taken to ensure that even one cell is not overcharged. $Ni\text{-}H_2$, Ni-Cd and NiMH are much less sensitive and can tolerate some amount of overcharging. While all battery chemistries are sensitive to operating temperature, $Ni\text{-}H_2$ cells are probably the most restrictive of operating temperature range. Typically, $Ni\text{-}H_2$ cells are limited to operating temperatures between -10°C to +25°C, whereas lithium-ion cells can be designed to operate anywhere from -20°C to +60°C.

Failure/Degradation	Mechanisms	Detection	Diagnosis
Battery failure	Mechanical separation, catastrophic battery failure-rupture of battery housing (open), cable failure	Battery current sensor	Inability of battery to deliver current during discharge, inability of battery to accept capacity during charge
Cell failure (short)	Manufacturing defect, containment failure	Cell voltage sensor, Temperature sensor	Unexpectedly low cell voltage, Unusually high cell temperature
Cell failure (open)	Electrolyte vent, cell case rupture, cell drying out	Current sensor, voltage sensor	Loss of amp-hour or watt-hour capacity
Cell degradation	Electrochemical aging, temperature effects, increase in internal resistance	Cell voltage or half-battery voltage sensor	Cell or half-battery voltage out of family
Battery electronics failure (charge circuitry)	Overcharge of cell/battery, over-discharge of cell/battery	Cell/Battery current sensor, temperature-compensated voltage sensor, temperature-compensated pressure sensor	Cell/battery voltage too high or too low (beyond design limitations), insufficient capacity

Table 3 – Battery Failure Mode Summary

Failure Recovery and Health Management - Battery failures are simple to detect and are typically not recoverable, so spacecraft are usually configured with several batteries to ensure reliability and continued operation. Isolating a failed battery falls to the PMAD system, using a combination of battery chargers and switchgear. Additionally, spacecraft operation and load schedules must be adjusted to account for reduced eclipse power capability or loss of charging circuitry. This rescheduling is typically performed by mission ground controllers, although automation capabilities will soon be needed as complex spacecraft and manned missions extend to Mars and beyond.

Battery health is measured today using existing sensors and the generated performance data is analyzed by ground personnel for long-range mission planning. The key performance measurements are battery capacity, measured in ampere-hours or watt-hours, and voltage, measured in volts. These measurements require accurate current and voltage sensors for the battery that are integrated over time during each charge/discharge cycle. These integrators must be reset with each cycle since "round-trip" energy efficiency is not 100%. An accurate ampere-hour reset requires the use of other parameters that indicate "full charge" such as charge termination voltage and delta-V measurements coupled with battery temperature, pressure, end-of-discharge voltages, and other performance trends over time.

Flywheel Energy Storage

Flywheels are an emerging technology for storing energy mechanically in a rotating mass. They are comprised of a high-speed rotor, bearings, and a motor/generator. Recent advances in composite rotor materials and magnetic bearings have allowed flywheels to approach the energy densities of electro-chemical battery systems, while providing much higher cycle-life for long-term operation. On Earth, flywheels are finding a market in medium-sized uninterruptible power supplies (UPS) for buildings, requiring much less maintenance than typical battery-based systems.

The interest in flywheels for aerospace applications lie in their potential for dual use in both storing electrical energy and providing momentum for spacecraft attitude control. For example, the Hubble Space Telescope (HST) uses six momentum wheels or "gyroscopes" to provide the accurate pointing of the HST to celestial targets, and a number of NiH_2

batteries to power the spacecraft in eclipse. A flywheel system could provide both of these functions, thereby saving mass and cost. Additionally, a flywheel has a projected life of greater than 15 years in low-Earth orbit, whereas batteries may have expected lifetimes of only 5-7 years.

Failure/Degradation	Mechanisms	Detection	Diagnosis
Rotor failure	Partial or Catastrophic mechanical failure	Magnetic bearing monitoring.	Sudden, extreme change in rotor balance detected in mag. bearing controls.
Magnetic bearing failure	Loss of drive power, coil failure, Sensor or controller failure.	Rotor position sensors	Disagreement between sensors and plant model observer
Motor/Generator	Coil failure open or shorted.	Current sensor, speed sensor	High or low currents detected, speed degradation when it should be increasing
Rotor degradation	Fatigue over time reduces tensile strength of the rotor. Creep (time and temperature effects).	Magnetic bearing monitoring.	Sudden changes in rotor balance can signify crack development and propogation.
Thermal	Externally heated, thermal control system failure	Infrared thermal detectors, stator thermocouples	Rotor temperature out of range.
Vacuum	Vacuum chamber leak, contamination by gases or dust	Infrared thermal detectors, watt-hour meters.	Unexpected rotor heating at high speeds, loss of roundtrip energy efficiency.
Power electronics and control	Mag bearing drive and control, motor drive inverter, generator active rectifier, digital controller	Current and voltage sensors	Loss of flywheel charge/discharge control.

Table 4 – Flywheel Failure Mode Summary

Failure Recovery and Health Management – While catastrophic failures of the flywheel rotor are obviously non-recoverable, partial failures and rotor degradation could be mitigated by operating the flywheel at reduced capacity (speed). Failures of the magnetic bearings may also be mitigated if limited in scope by use of fault tolerant control algorithms. Certain thermal and vacuum problems can be accommodated by reducing the maximum operational speed of the rotor.

Aside from failures, the health of the flywheel rotor can be measured. It has been shown that the initiation of flywheel rotor cracks can be detected using the magnetic bearings to detect changes in the rotor balance over time [Sonnichsen]. Additionally, much can be inferred from rotor temperature profiles and roundtrip efficiency measurements. Finally, since a flywheel energy storage system will most likely perform the additional function of spacecraft attitude control it is important to consider what effect the degradation or failure of one flywheel might have on the complete system. The complexities involved require that on-board controllers have the necessary information and flexibility to make these adjustments without requiring input from ground controllers.

Power Management and Distribution (PMAD)

The power management and distribution (PMAD) system is comprised of regulators, converters, switches, cables, and controls necessary to deliver power from the energy suppliers (sources) to the energy consumers (loads). PMAD systems have generally relied on redundant hardware in order to mitigate component failures. PMAD components are comprised of power electronics that can fail without degradation and/or can be difficult to detect degradation due to the high-bandwidth operation. This section is broken down into two major parts – the power management sub-system comprised of converters and regulators that condition the power, and the distribution sub-system comprised of switchgear and cables responsible for delivering electrical power to the loads.

Power Regulators and Converters

Power regulators and converters are sometimes required to regulate and condition the electrical power generated by the sources before being delivered to the user loads. The complexity and the topology of the power system will determine the amount of regulation and conversion necessary. For example, many space satellites employ direct energy transfer (DET) system such that the solar array is tied directly to the battery, which in turn is tied directly to the user loads, without any means for regulation or conversion. These systems are generally simple in nature and short-lived, where source and storage element operation remains relatively constant over the short life of the mission. At the other end of the spectrum, the International Space Station (ISS) employs solar array regulators, battery charge and discharge regulators, and dc-to-dc converters in order to precisely control the quality of the power delivered to the user loads – much like power utility systems on Earth.

Table 5 summarizes the key failure modes for regulators and converters found in systems employing solar arrays, fuel cells, batteries, and/or flywheels. As such, it is assumed that the majority of these are dc-to-dc converters and regulators.

Failure/Degradation	Mechanisms	Detection	Diagnosis
Power converter loss of output power	Internal failure, commanded off, loss of input voltage	Input and output voltage, output current, on-off command sensor	Loss of output voltage with good input voltage, low currents, and verified on command.
Power converter loss of output regulation	Internal failure, input voltage out of range, load out of range.	Input and output voltage sensors, output current sensor	Output voltage out of expected regulation range.
Excessive power converter noise	Internal failure, passive filter failure, system instability.	High frequency Input voltage and current sensor	Output voltage out of expected regulation range.
Motor drive failure	Internal power electronics failure, motor load failure.	Voltage and current sensors	Loss of output current and/or output voltage.
Battery charger failure	Internal power electronics failure, sensor failure.	Battery current sensor	Battery charge current zero
Battery discharger failure	Internal power electronics failure, sensor failure.	Battery current sensor	Battery discharge current zero
Solar array regulator failure	Internal power electronics failure, sensor failure.	Array current sensor	Solar array current zero

Table 5 – Power Converter and Regulator Failure Mode Summary

Failure Recovery and Health Management – Most power converters and regulators are intolerant to internal failures and will lose all functionality. As such, power systems rely on redundant hardware to ensure power regulation and conversion following one or multiple failures. However, there are certain topologies that can experience an internal, power electronic or controller failure and still provide power to a load. Some examples are the boost regulator and the series connected boost regulator. Other topologies require extra protection so that internal failures do not propagate to other parts of the system. For example, full bridge dc-to-dc converters can fail such that the input is shorted, requiring either a fuse or current limiting switch on the input.

Power electronic health management is currently not in use since it is difficult to detect degradations in these high-speed devices. First, component degradation can involve miniscule changes in relation to steady-state operation, making measurement very difficult. Also, devices can fail without any detectable degradation at all. [Orsagh] Recent developments in the digital control of power electronics has now made it possible to detect small changes in the "plant" that can point to degradation in the individual components. Additionally, stress events can be logged to help assess remaining life. As digital controllers become more prevalent, the ability of a power converter or regulator to determine its "health" may become a reality. Coupled with more modular systems, these new technologies offer many opportunities for active health management of the EPS.

Distribution switchgear and cables

Distribution switches are used to control power delivery to the loads, and to isolate faults to small sections of the power system. These switches can be electro-mechanical relays, semiconductor switches, and even simple devices like fuses. Distribution switches can either fail in the "open" or "closed" state, and it is impossible to tell that a failure has occurred until the switch fails to respond to a command to change states. Cables and connectors include all power distribution cables such as large primary distribution cables, smaller secondary distribution cables that feed the individual loads, and the large and small connectors required to terminate the cables.

Failure/Degradation	Mechanisms	Detection	Diagnosis
Mechanical relay fails open	Coil/latch failure, contact failure	voltage sensor, aux. coil switch sensor	Coil activated but output voltage not equal to input voltage
Mechanical relay fails closed	Coil/latch failure, partial or full contact weld failure.	voltage sensor, aux. coil switch sensor	Cannot open relay and coil drive determined to be good.
Mechanical relay contact degradation	Contamination of contacts via outgassing of lubricants or repeated arcing and pitting during high current switching	Contact voltage sensor, current sensor	Increased voltage drop across the switch vs. current through the relay
Semiconductor switch fails open	High currents damage semiconductor or metal contacts.	voltage sensors (input, output, and gate drive)	Switch does not turn on (input voltage seen at the output) with a good gate drive signal
Semiconductor switch fails closed	High voltage "punch-through" damage of semiconductor. Radiation damage prevents turn-off	voltage sensors (input, output, and gate drive)	Switch does not turn off (output voltage goes to zero) with a low gate drive signal
Semiconductor gate drive degradation.	Radiation exposure lowers MOSFET threshold voltage. High temperature affects switch on resistance	voltage sensors (input, output, and gate drive), temperature sensors	Switch turns on with a low gate drive signal. Switch voltage drop higher than expected, high switch temperatures.
Cables/connectors open circuit	Mechanical damage/failure	Distributed voltage sensors	Voltage at one end of cable is vastly different than the other end.
Cables/connectors short circuit	Mechanical failure of the insulation. Mechanical cable failure.	Current sensor	Very high current detected at steady state (several milliseconds)
Cables/connector soft fault (arcing, leakage)	Mechanical failure of insulation.	High frequency current sensors. High accuracy current sensors.	Arcing detected by 2-5kHz noise in current sensor. Leakage detected by difference in current sensor at either ends of the cable.
Cables/connector degradation	Mechanical wear, environmental contamination	High accuracy voltage and current sensors	Increase in conduction loss detected using current and voltage sensors.

Table 6 – Power Distribution Failure Mode Summary

Failure Recovery and Health Management - Failures of distribution switches, cables, or connectors can only be mitigated by isolating the fault and routing the power via another physical path. Open failures of switches are a “safe” failure but a major concern since they prevent power from being delivered to user loads. Operational systems must be designed such that backup paths and redundant hardware can mitigate “open” switch faults.

Shorted “closed” failures of distribution switches are potential safety hazards and will propagate any load faults to a larger area since upstream switches will be required to respond to load faults downstream of the failed switch. This means instead of isolating a fault to a single load, load faults could now affect a number of loads being fed by larger upstream switches.

Health management of power distribution hardware is almost non-existent. There are some emerging capabilities in cable arc fault detection [Gonzalez], but most all other failure and degradation modes are currently uncovered in aerospace distribution systems.

Review of Current Power System Health Management

In 2004, during the Next Generation Launch Technology (NGLT) Health Management Technology (HMT) program, a knowledge acquisition effort was undertaken that gathered information from domain experts at the NASA Glenn Research Center in the power subsystem area in regard to HM technologies. From this information, the state-of-the-art in health management (HM) technology for space-based power systems was determined to be an under-developed technology area that must be improved upon in order to achieve the nation’s space exploration goals.

A comprehensive list of HM power system examples will not be presented, because it would be too difficult to thoroughly and adequately represent government, industry, and academic interests without producing an exhaustive survey paper. Instead, HM-like technologies that have been applied to already successful space power systems will be presented. Examples of HM-like technologies that have been implemented on mature space-based power systems include: the Hubble Space Telescope (HST), the International Space Station (ISS), and the Shuttle. In general it was found that the electrical energy sources and storage elements employed basic levels of HM, while power management and distribution systems were sorely lacking in even basic HM methods.

Hubble Space Telescope

The HST electrical power system consists of five major components: the solar arrays, nickel-hydrogen batteries, diode box assembly, power control unit, and charge current controller [Waldo]. HST uses a direct energy transfer power system topology whereby the solar panels are connected (through intermediate equipment) directly to the batteries. The batteries charge during the sunlit portion of the orbit and then discharge to supply power to the observatory when the solar panels are not illuminated.


The Hubble Space Telescope

Gradual loss of charge capacity in response to charge and discharge cycles is a normal aging effect for batteries and was anticipated for HST. Energy capacity has been continuously monitored since HST’s launch. The batteries have also been periodically reconditioned, which is accomplished by removing a single battery from service and then cycling it through a deep discharge to an essentially discharged state followed by a full recharge. Battery reconditioning, when performed correctly, helps to restore some capacity to aging batteries. By careful monitoring of the amount of energy extracted during the discharge cycle, determination of battery capacity is also possible. [NAP]

The HST uses a pair of articulated solar panels on each side of the telescope to generate power when the panels are illuminated by the Sun. Performance of the solar arrays is continuously monitored by the ground-based HST operations team in order to track the average loss of power over time. The drop in power output due to a combination of accumulated damage from meteoroid and debris impacts, cracking from thermal-cycling, and damage to the solar cells from radiation, has been within the expected range of performance degradation. [NAP]

These HM techniques have been used to predict future capabilities and adjust mission operations. This has proven useful in extending the life of the HST as planned Shuttle servicing missions have been delayed by the Columbia accident in 2003 and continuing safety concerns.

Additionally there are component-specific hardware safety features that provide protection for the power system in the following manner. The diode box assembly has a diode isolation component that protects the solar panel assemblies. There is also an arc suppression network that protects the power conditioning unit during battery charging. The power conditioning unit houses the battery conditioning hardware, bus and external power isolation diodes, and overvoltage protection electronics. The original charge current controller has four voltage/temperature settings that allow for different charging conditions.

Operation of the charge current controller was modified to offset changes in the batteries due to aging and thermal heating. A device called the voltage/current improvement kit (VIK) was designed to charge the batteries to their optimal cutoff voltage to prevent overcharging and overheating [GSFC]. They were installed in December 1999 during Shuttle Service Mission 3A (STS flight 103). Since overcharging is no longer possible, these charging kits will improve the life span of the batteries. Other software based HM applications have been considered as research projects, such as an expert system for the electrical power system that monitors overall health and safety, detects performance trends, and detects anomalies [Eddy].

International Space Station

The electrical power system for the ISS is primarily made up of the solar array wing, nickel-hydrogen batteries, direct current switching unit, battery charge/discharge units, and dc-to-dc converter unit [Hajela]. Since the batteries provide the only power to the space station when sunlight is unavailable, their reliable and safe operation are critical for mission success. Each battery is made up of two orbit replaceable units (ORU), and each battery ORU has 38 nickel-hydrogen battery cells. Monitoring of the batteries is performed by manually reviewing on-orbit data back on Earth. Parameters that are measured and sent back include the following: cell-to-cell temperature, ORU voltage, cell voltage, and ORU pressure. From this data, health status can be determined and anomalies detected. However, since this is done manually, it is a time-consuming process. Automation of this process using available commercial software has been presented [Aaseng]. This would improve the timeliness, accuracy, and consistency of fault diagnosis. Additional health assessments of solar array performance are similarly conducted by mission operations on the ground using down-linked telemetry data.

The International Space Station

Shuttle

The electrical power system for the Shuttle contains the following three subsystems: fuel cell power plants, electrical power distribution, and power reactant storage and distribution [NSTS]. The complexity of the Shuttle prohibits a list of all its safety features. For the most part, detection of anomalies is performed by reviewing data from the caution and warning system and analyzing data from the sensors. Again, this is a labor-intensive method that can lead to errors and incomplete analysis of the system's health status. While an Advanced Health Management System (AHMS) for the space Shuttle main engine has been proposed, there is nothing similar for the electrical power system.

The Space Shuttle

Aeronautics

For aeronautic applications, fault detection, isolation, and recovery (FDIR) systems are typically designed for the engine, which, in concert with a variety of electrical generators, is the main source of power for the aircraft. The electrical system, although a necessary component, is not as extensively monitored as the mechanical, hydraulic, and pneumatic systems. Therefore, examples of aviation EPS HM applications are rather limited. Traditionally, problems with electronic components are discovered using built-in-tests, or they are replaced during scheduled maintenance procedures before they become a risk. In addition, they are often contained in redundant configurations that prevent catastrophic failures from occurring in the first place. However, these approaches to maintaining EPS safety are liabilities to the overall cost, mass, and maintenance of the aircraft.

Aviation state-of-the art for EPS HM applications is probably best captured in the inspection and maintenance procedures that use post-flight data to isolate failed, damaged, or fatigued components. Since most post-flight inspection is still based on routines and schedules, a condition-based maintenance program that only replaces components as needed could reduce turn-around-times and their associated costs. New HM technologies, especially for the electrical power system, would be required for the development and implementation of such a program.

Currently the government is defining its future in aeronautics much like it did when it defined its vision for space exploration. Most likely, the aeronautics vision will include the current trend, which is already being implemented, toward a More Electric Aircraft (MEA). The design of the MEA replaces traditional mechanical, hydraulic, and pneumatic components and systems with electric ones. The anti-ice, actuation, auxiliary power unit, and environmental control system are just a few examples that would be replaced by electric systems. Presently, MEAs are being designed and developed by the Boeing Corporation (7E7), Airbus (A380), and the USAF (Lockheed Martin JSF). The quality of the power generated, the integrity of the distribution system, and the reliable operation of electrical-dependent systems and components can best be achieved by incorporating HM technologies into the design and development process.

The MEA will require reliable, high quality power, and a HM system that is designed and developed in parallel with the aircraft will help to meet this requirement. It should be easier to implement and put into practice these HM technologies, because the necessary testing and validation that is required for flight qualification should be easier and cheaper than for space-based systems. As an added benefit, much of the software algorithm development should be applicable to both types of applications.

Future Power System Health Management

As has been shown, energy sources and storage elements already employ basic HM techniques in order to assess health and plan future power usage. This is possible because health trending of these power sources generally happen over long periods making ground-based data analysis and verification possible. However, the power electronics that make up the power management and distribution (PMAD) system has not taken advantage of HM techniques. Since it is expected that future aerospace power systems will increasingly employ high-speed digital controllers and data networks for effective and safe operation, new HM capabilities will be available to the PMAD component and systems. Below is a discussion of potential improvements that can be realized in the health management capabilities of future electric power systems.

Design Considerations

For the most part, safety and reliability have been addressed in the past by using hardware-related safety mechanisms, redundant components, device specific built-in-tests (BITs), and line-replaceable units (LRUs). For today's proposed power system applications, the practices listed above do not solve the overall HM problem and can add to the cost and weight of the designed power system. However when HM is added to a system, it should not be retrofitted to the final design but instead developed early in the design phase where it can be used to support and benefit the overall design. For instance, considering the HM system earlier on could impact sensor locations that are used for fault detection and isolation.

Since the planning of a health management system would be incorporated early into the system design, this occurs well before there is any test data available for the proposed system. Therefore, a virtual environment of the system that permits extensive testing is essential. In addition, for a power system it is possible to build ground-based facilities that can support the testing and demonstration needs for a full-scale system. The cost of building, maintaining, and utilizing the type of test facility that is representative of a power system in a space environment is possible and would also serve to support the modeling and simulation tools that are developed. Furthermore, the test facility would also facilitate the testing of new component hardware that is developed for HM applications, which is discussed in the next section.

Hardware Advancements

Health management benefits can be realized at different hierarchical levels throughout the power system. In most cases, processing power and communication bandwidth required will determine what functions can be performed at what hierarchical level.

At the lowest levels, direct digital control of the power electronics and sensors in the EPS requires the highest bandwidth and processing speed in order to deal with the sub-millisecond events and provide the control performance expected from power electronics. An example of this low-level, localized control would include the intelligence that could be found in power electronic building block (PEBB) devices. A PEBB device is expected to have dedicated, high-speed digital and analog controllers in order to gather sensor data and make control decisions within several microseconds. Such control would include safe-operating area protections to ensure that the switch did not experience over stressed conditions that threaten its health and continued operation. These include detectable and controllable events such as over-current protection, single event upset (SEU) protection, and thermal overload protection. Additionally, the PEBB controller is expected to have the bandwidth necessary to capture and record short-term, non-controllable stress events as they occur, and provide a health assessment based on the number and frequency of these events. This capability alone would be a significant improvement over current capabilities.

Intelligent Software

The next hierarchical level of intelligence is that of the power electronic functional module such as dc-dc converters, regulators, and switchgear. At this level, health monitoring algorithms can be used to estimate the health of the module, allowing additional algorithms to actively manage power loading amongst modular components. [Button] Additionally, soft fault detection capabilities requiring digital signal processing and analysis can be implemented in distribution switchgear. One example of an emerging power electronics HM technology is that of active power quality and stability control. Active stability control is a technique where a digitally controlled power electronic device can vary its control loop as changes in the “plant” occur over time. These detectable changes can then be used to infer the health of the device, leading to new HM techniques. [Miao]

Finally, intelligence can be applied at the system level to bring the benefits of health management to the entire electrical power system. At the system level, health management depends largely on communication networks gathering health data from all power system components in order to analyze and inference system health status. The bandwidth of data collection can be much slower than at the component and device level since the events that affect the entire power system are detected and acted upon at a much slower speed so as not to interfere and interact with the higher speed control taking place at the component levels. New health management functionality that can be achieved at the system level includes automated fault detection and recovery, mission planning, and energy management.

Automated fault detection and recovery requires system awareness and advanced computing algorithms to determine the optimal corrective actions to take to mitigate the fault. Faults can take the form of hard faults - source failures, distribution switch failures, load converter failures – or soft faults such as low-level arcing faults, corona discharge, shunt (leakage) faults, and series (resistive) faults. Once a fault has been identified and isolated at the local level, advanced optimizing algorithms would autonomously reconfigure the system topology in order to mitigate the fault. Ideally, these algorithms could pre-plan for failures and have optimized corrective actions pre-determined when a fault occurs. This on-board automation requirement is essential if the vehicle location requires hours for round-trip communication with ground-based mission controllers.

Automated mission planning algorithms could include priority load shedding or even free market economy algorithms that achieve maximum mission functionality in the presence of degraded power capability. Finally, system health management can also enable system-wide energy management in order to extend the life of the mission and optimize the safety and performance of the power system in the presence of failures and degradations. These advanced algorithms will be required, especially if the power system uses a high degree of modularity and a highly reconfigurable distribution architecture.

Conclusion

Aerospace electrical power systems (EPS) are comprised of four major subsystems – energy generation, energy storage, power management, and power distribution. Each system has a variety of unique failure and degradation modes, presented above, that can negatively impact safety and mission capability. While all four subsystems are required for the effective operation of the EPS, a review of several state-of-the-art aerospace vehicles shows that health management techniques have generally been limited to the energy sources and storage elements. Furthermore, these functions have been performed off-line by mission planners for the sole purpose of predicting future energy availability and mission life. Recent advances in digital control and modularity of power electronics enable new capabilities for health management of the power management and distribution (PMAD) subsystems. Finally, as new aerospace vehicles and platforms are developed for space exploration, the inclusion of HM techniques and automation early in the design cycle will become critical to the long-term safety and success of these missions.

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